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The Design and Application of Correlation Control

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This article describes the theory, design and application of correlation computing devices. It shows how they are used with feedforward and feedback loops to produce systems with adaptive properties. Examples are given of their use with steel strip rolling mills and pipe welding mills.

■ Closed loop regulating systems may be regarded as being in the form shown in Fig. 1. A regulating device, RD, notes variations in the output of the process and feeds back signals into the process which act to eliminate the errors noted at the output. Fig. 1 also shows that a second loop can be added. It consists of a computing device, CD 1, which measures disturbances to the process and "feeds forward" signals to the regulator.

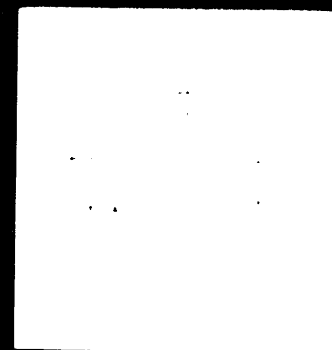
If we consider the application of these principles to a steel rolling mill, for example, we will note that the feedback loop is handicapped by a transportation lag between the actuator (the rollers) and the steel thickness gage located on the exit side of the rollers. The feedforward loop responds to measurements made on the steel before it enters the rollers and in consequence is required to predict proper corrective action for the instant when a measured point on the steel passes through the rollers.

Feedforward systems can do without the feedback loop completely, and produce, in theory, error-free performance providing there is no drift within the body of the process. In the case of the steel strip roller, drift may take place due to wear on the rollers or their bearings, changes in metal temperature, etc. Where drift occurs within the process, feedback measurement becomes desirable.

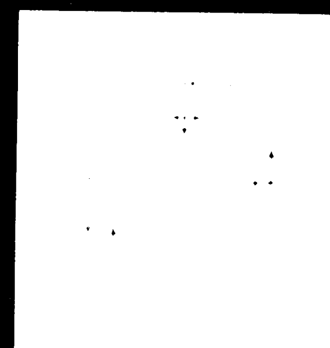
Fig. 2 shows a second computing device, CD 2, applying a corrective signal to CD 1. It determines the direction and magnitude of process drift where several disturbances exist, requiring several feedforward computing devices. It becomes essential that the feedback signal to the feedforward computers relate the variations in the output with the disturbance handled by a given computer. To do this, cross-correlation is required. Therefore CD 2 is shown as a device which uses the variation in the load as an input signal as well as the feedback signal from the output of the entire system. As a result, the drift correction which CD 2 applies to CD 1 relates only to the disturbance measured by CD 1.

In most processes only one disturbance need be reckoned with in a feedforward loop. The influence of other disturbances may be minimized by an ordinary feedback system. Assuming that the feedforward computer properly matches the transient characteristics of the process, all that the control system requires is an adjustment of the ratio between the magnitudes of the feedforward and feedback corrections.

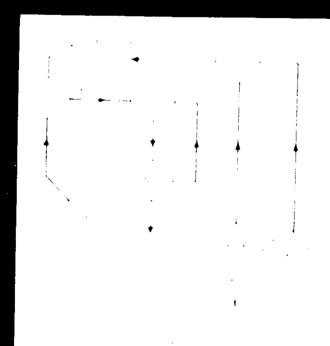
This is accomplished by varying



1 *A process controlled by feedback through a regulating device (RD). Computing devices sense load variations (CD1) in a feedforward loop.*



2 *A correlation computer (CD2) added to the system in Fig. 1, can adjust transformation ratio or gain of CD1.*



3 *This diagram illustrates the basic configuration of a strip rolling mill following the scheme outlined in Fig. 2.*

the gain of the feedforward computer's output according to the integral of the system's output error. Looking at Fig. 2, CD 2 need not cross-correlate, but only adjusts the gain of CD 1 according to the integral of the error. CD 2, therefore, need consist of just an integrator and multiplier. Thus, the steady state value of the error's integral establishes the required magnitude of the output of CD 1.

However, the process may be subjected to disturbances other than the one measured by CD 1. These can be considered random noise. This noise will cause a continuous variation of the gain of CD 1 through its action on CD 2.

The influence of this noise may be considerably reduced if the changes in the gain of the feedforward computer take place only when the magnitudes of the system's output error and the load disturbance vary simultaneously. To fulfill this requirement, CD 2 must compute the pseudo-cross-correlation function

$$Y\ (t) = \int_{\circ}^{t} \Delta\ x\ (t)\ \Delta\ y\ (t\text{-}Y)\ dt$$

where y is the time lag of the process Δ x the error at the output and Δ Y the disturbance. Thus, CD 2 takes on the form of a correlator and to mechanize the above equation, contains time delay, multiplying, and integrating units of an electronic or electromechanical type.

Design of a Correlator—An electromechanical approach to the design of the correlator consists of a two-phase ac fractional horsepower motor and two amplifiers supplying 90° phase shifted ac voltages which are proportional to the value of the error, Δ x, and the disturbance Δ Y. Consequently, the torque and speed of the motor are proportional to the multiplication of these two voltages, and the total displacement of its shaft is proportional to the integral of this multiplication. CD 2 may be used to adjust the gain of CD 1 through the use of suitable gear reduction between the output of the motor shaft and a potentiometer controlling the magnitude of the output of CD 1.

The action of the above arrangement will be to increase the magnitude of feedforward correction with positive correlation of output error and load disturbance, and to lessen the magnitude of feedforward correction with negative correlation.

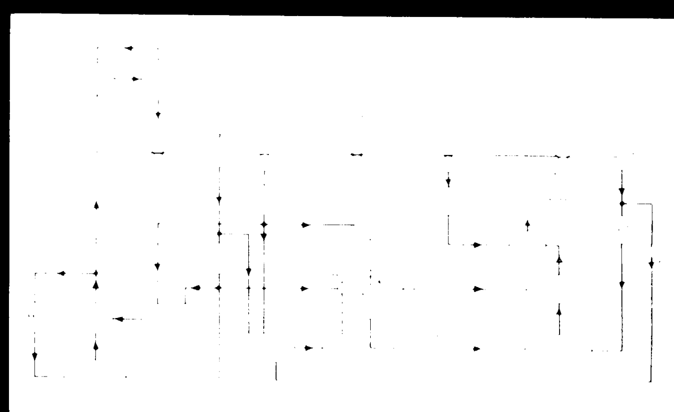
The gain of the feedforward controller is held at a constant value only when the output error drops to zero. Control systems with correlation regulation can be applied to many different processes.

Strip Rolling Application—Fig. 3 illustrates such a system for the reduction of variations in steel strip thickness caused by variations in temperature during hot rolling.

Temperature variations are measured by the pyrometer RPI located on the delivery side of the mill. A voltage from the pyrometer proportional to temperature is applied to CD 1, a multiplier. The output voltage of CD 1 is the command signal to the positional servo system SS of the screw down drive, M. CD 2 in this system accepts two voltages: Δ T_2, temperature; and Δ **h**, thickness variation. These variables are measured simultaneously on the exit side of the mill by RP 2, a pyrometer, and TG, an X-ray thickness gage.

Figure 4 shows a steel strip rolling mill control of a type commonly found in the United States, to which correlating control has been applied. The system has coarse and vernier regulators. The coarse controller changes roll setting of the stand I in accordance with strip thickness variations measured by the thickness gage TG 1. The vernier regulator controls the strip tension before the last stand of the mill by changing the speed regulator setting. This tension acts to thin the strip even further. Fig. 4 shows that TG 1 is the pickoff for a feedback regulator with Stand I acting as the plant or actuator element. Because of transportation lag, this loop is of the incremental advance type. TG 1 is also used to control the tension produced by Stand II in a feedforward system. The transportation lag between the reading of TG 1 and the movement of the strip to TG 2 is accounted for by a delay unit consisting of a magnetic drum, MD, whose speed of rotation is kept synchronous with the strip movement.

Even though Stand I is in a feedback loop with incremental or impulse type correction, the correlation computer described for use with feedforward systems can be applied with profit here. A parameter in such a loop is the magnitude of correction which each corrective impulse will affect. The magnitude of this correction is the gain of the servo.



4 *A rolling mill in which the basic scheme of Fig. 3 has been expanded to utilize the correlation computer for both feedback and feedforward control.*

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Figure 4 shows how the magnitude of each corrective step can be varied by correlation correlator CD 2 and the multiplier element ME. Since the regulating actions are given in the form of pulses, CD 1 consists of a memory MU which stores the value of the last regulating action S until the next measurement of strip thickness is taken. Hence, this device correlates increments of error with increments of corrective action.

To improve the performance of the vernier regulator, the second correlator may be used as it is shown in the right hand side of Fig. 4 as CD 5. This correlator computes the psuedo-cross-correlation function of the strip thickness variations after the first and last stands. The signals for this correlation are obtained from thickness gages TG 1 and TG 2. A further refinement of the system uses another computing device, CD 3, to position the head of the magnetic drum, RcH, to adjust the time delay for the vernier control for an optimum value.

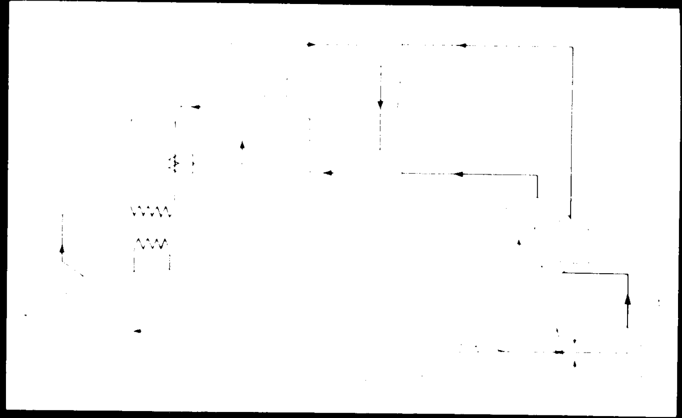
A Pipe Welding Application — Another example of a control system utilizing the correlation regulator is shown in Fig. 5. The system illustrated is for the regulation of welding current in a pipe mill.

The quality of the electro-welded seam of a pipe is determined by the temperature of the seam at welding. This temperature is the function of many variables. The values of welding current and pipe wall thickness are the most important variables. Strips from which the pipes are formed are hot rolled. Their thickness varies as much as 20%. These thickness variations cause changes in welding temperature even when the current is constant. Systems have been used in America which measure the thickness of the metal before forming so as to later regulate welding current. A time delay accounts for the transportation lag between the thickness measurement and the welding operation.

Such systems can be improved by including a correlator which selects the proper gain of the current regulating control so as to obtain uniform seam temperature.

Fig. 5 shows that a voltage proportional to temperature variation from the setpoint and a second voltage proportional to metal thickness variation are applied to the correlator. A magnetic drum is used to account for transport time.

The mathematical investigation of correlation control systems has not been elaborated to any great detail, although the solution of the equations of the system have been given for a particular simple case when step disturbance is applied. ■ ■



5 *The application of correlation computer control to welding pipe operations.*